PROJECTED LONG-TERM PERFORMANCE OF HOPI ARSENIC MITIGATION PROJECT (HAMP) WELLS 2 AND 3 HOPI RESERVATION, ARIZONA

by

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prepared for

Bohannan Huston, Inc.
Albuquerque, New Mexico
and
Department of Health and Human Services
Public Health Service
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INTRODUCTION

In late 2013 and early 2014, two water-supply wells were drilled on Hopi lands for the Hopi Arsenic Mitigation Project (HAMP). The locations of the wells, HAMP Well No. 2 and HAMP Well No. 3, are shown on Figure 1, and full information about the drilling and testing can be found in the well report (Fritz et al., 2014). The purpose of the present report is to describe an analysis and projection of future performance of the wells in terms of production capacity and water quality.

DESCRIPTIONS OF WELLS

& D Aquifer

The two wells were drilled, completed, and tested between June 2013 and June 2014. HAMP Well No. 2 was completed in the N aquifer at a total depth of 2,180 ft, with a non-pumping water level of 445 ft, and was tested at 300 gallons per minute (gpm). Well No. 3 was completed in the N aquifer at a total depth of 2,241 ft, with a non-pumping water level of 451 ft. The pumping test was at 321 gpm. Both wells have very high efficiency, with specific capacity close to the theoretical values calculated from transmissivity, storage coefficient, and well-construction. Full information about both wells can be found in the combined well report (Fritz et al., 2014).

AQUIFERS AND AQUIFER PROPERTIES

Both wells penetrated water-bearing units in the Cretaceous-age Mesaverde Group, the Cretaceous-age beds of the D aquifer, and the Cretaceous- and Jurassic-age units of the N aquifer, and both were completed to produce from the N aquifer. The focus of this report is on the N aquifer, and potential leakage into it from the overlying D aquifer. + Annular space

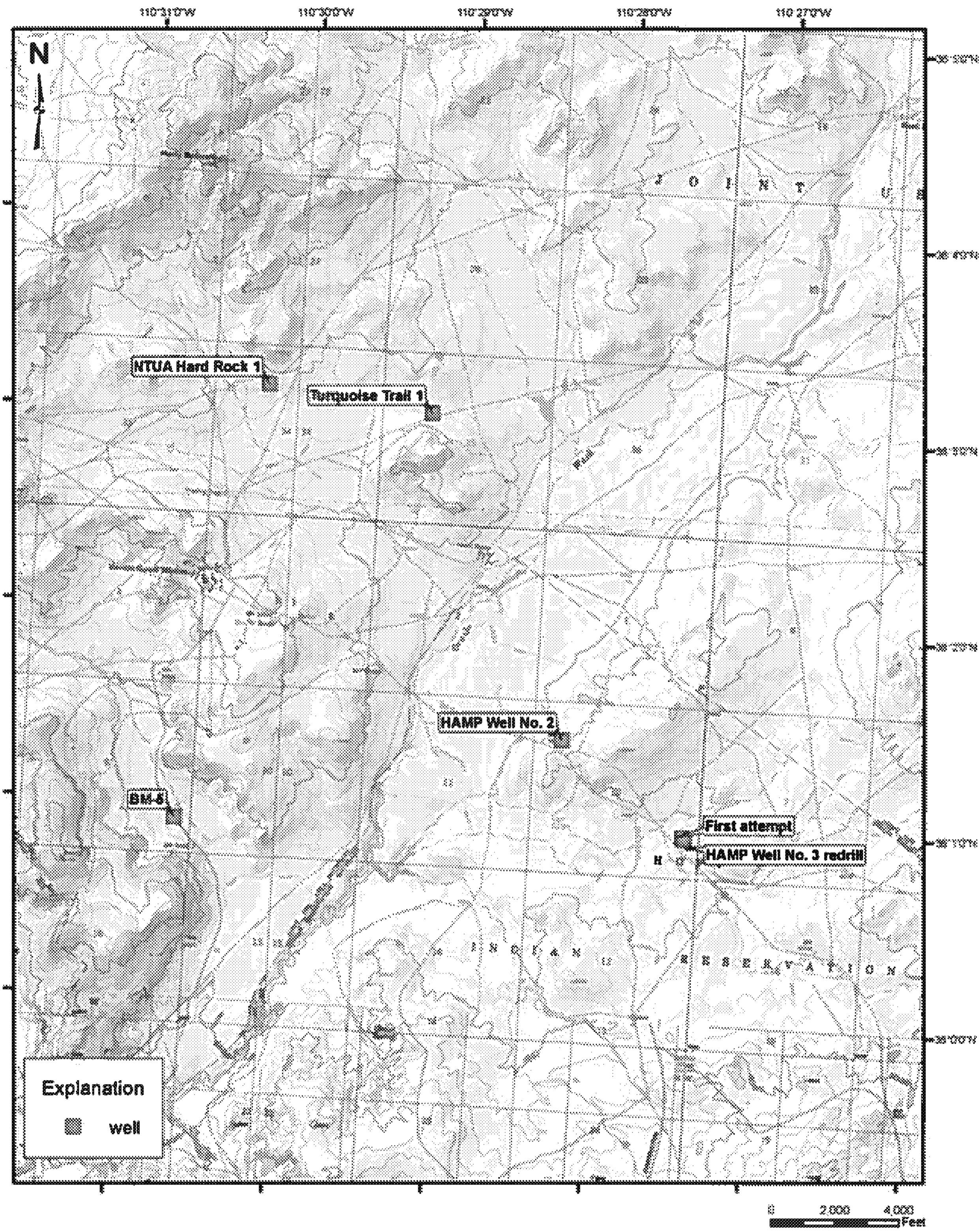

Figure 1. Map showing locations of HAMP wells and selected other wells mentioned in text.

D Aquifer

The D aquifer includes the Dakota Sandstone, a gray, fine-grained well-cemented sandstone with minor silt and clay interbeds and minor coals, and the Entrada Sandstone, a gray to brown, very silty to clayey sandstone. The D aquifer was found in the interval 890 to 1,590 ft in HAMP Well 2, and 940 to 1,643 ft in HAMP Well 3. A sample taken from a temporary completion in the D aquifer in HAMP Well 2 had an arsenic concentration of 2.9 micrograms per liter (µg/L), somewhat less than the concentrations in the zones sampled in the N aquifer, and a total dissolved solids (TDS) concentration of 1,390 mg/L. No aquifer properties were determined for the D aquifer.

Confining Units

The confining unit between the D aquifer and the N aquifer is the Carmel Formation, a reddish-brown to gray sequence consisting primarily of siltstones with some sandstone and clay. The Carmel was 80 and 82 ft thick in the two HAMP wells. No water sample was taken from the Carmel, and no aquifer properties were determined.

TT #2 — 2170 − 1670 = 500 ft
TT #3 — 2215 − 1725 = 590

N Aquifer

The N aquifer as completed in the HAMP wells was essentially the Navajo Sandstone, a brown, silty, fine-grained sandstone, between 1,670 and 2,170 ft in HAMP Well 2 and 1,725 and 2,215 ft in HAMP Well 3. Arsenic concentrations in waters from the two HAMP wells, at the end of pumping tests in the completed wells, were 4.7 (40) and 4.2 (60) µg/L respectively, and TDS concentrations were 167 and 200 milligrams per liter (mg/L) respectively. Samples taken from temporary completions of HAMP Well 2 in three separate zones of the N aquifer had arsenic concentrations of 4.1 to 4.8 µg/L.

Transmissivity and Storage Coefficient: The HAMP wells are in the southern part of the area of the N aquifer, in which confined storage conditions prevail (Fig. 2). Transmissivity of the aquifer at Well 2 was estimated at 533 ft^2/day, and storage coefficient at 0.00090, and transmissivity at Well 3 was estimated at 564 ft^2/day with a storage coefficient of 0.00086.

Leakage: Leakage of poor-quality from the D aquifer into the N aquifer is a potential problem. The pumping test of Well 2 suggests the presence of a leaky boundary condition, but the test of Well 3 does not. Both Well 2 and Well 3 are very close to the boundary between the area of the N aquifer in which leakage through the overlying Carmel Formation occurs, and the area in which leakage has not been recognized (Fig. 2; from Lopes and Hoffman, 1997, fig. 4). These authors have determined that the two areas can be identified by water chemistry in a number of ways, including radioactive and stable isotopes, and major ions. In terms of major-ion chemistry, waters from wells located north and west of the leakage boundary, where leakage is not thought to occur, contain significant concentrations of calcium, whereas waters south and east of the boundary, where leakage has been recognized, have very low calcium concentrations. The final samples from both Well 2 and Well 3 contained less than 1 mg/L calcium, indicating that they are within the leakage area.

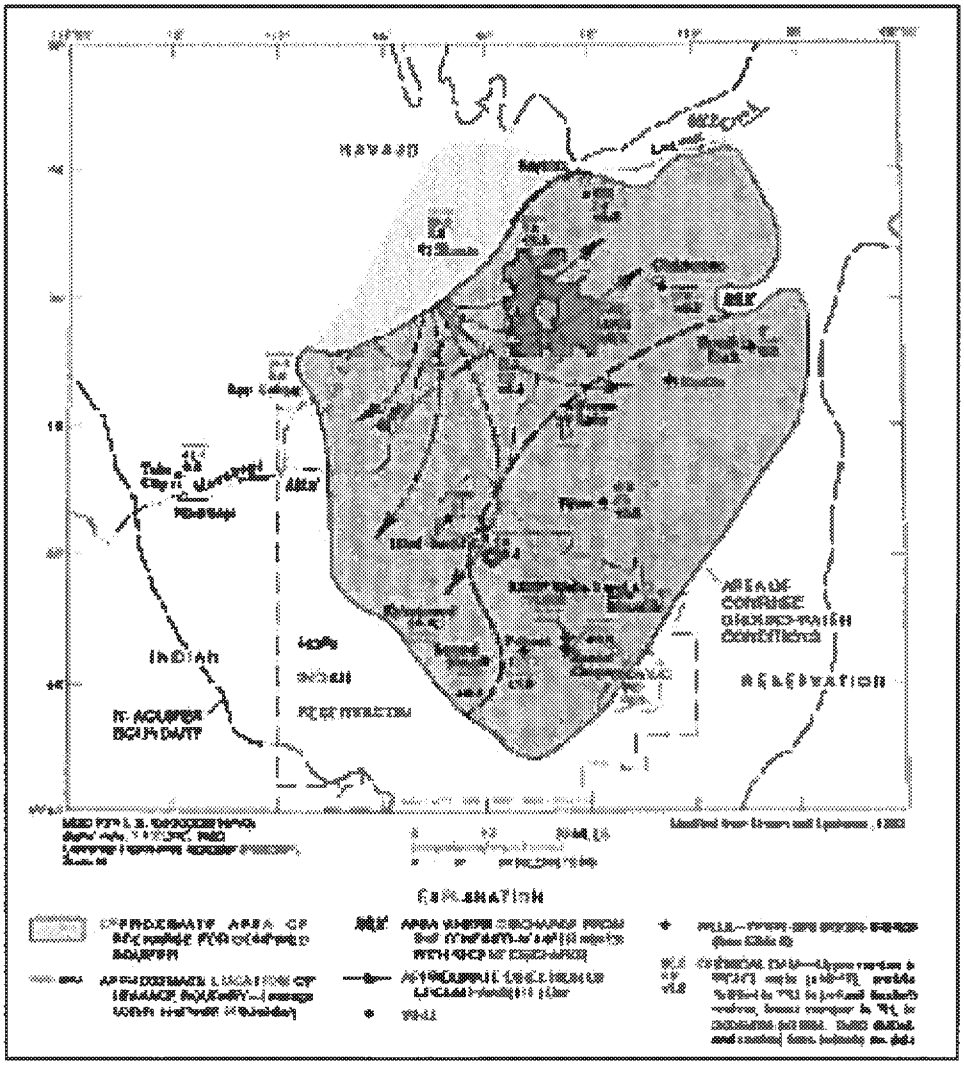

Figure 2. Flow directions and area of possible leakage in the N aquifer, Black Mesa area, Arizona (reproduced from Lopes and Hoffmann, 1997, fig. 4). Leakage occurs in the area southeast of the boundary shown. HAMP wells area indicated by red symbol.

On the other hand, concentrations of fluoride and chloride in the leakage area are relatively high (Lopes and Hoffmann, 1997, p. 10), but in HAMP Wells 2 and 3 these constituents are present at very low concentrations: fluoride is 0.15 and 0.16 mg/L, and chloride is <5 and 7.4 mg/L in the two wells, respectively. For comparison, the NTUA Hard Rocks well, exactly on the leakage boundary as it is drawn by Lopes and Hoffman, has calcium at 0.76 mg/L, similar to HAMP Wells 2 and 3, but fluoride is at 1.4 mg/L and chloride at 40 mg/L, much higher values than in the HAMP wells.

PROJECTED WATER LEVELS AND WELL CAPACITY, HAMP WELLS

Regional N-Aquifer Pumping and Predicted Drawdown

Historic Regional Pumping: The U.S. Geological Survey (USGS) has maintained a well-production and water-level monitoring program in the Black Mesa Basin for many years, with progress reports beginning in 1978 and on an annual basis since 2004 (Macy and Unema, 2013). The N-aquifer wells monitored for production are shown on Figure 3, and the annual amounts produced are summarized graphically in Figure 4, both reproduced from the most recent of the annual monitoring reports. Aggregate pumping from the N aquifer was small before 1970, then rose irregularly from about 1,170 acre feet per year (ac-ft/yr) in 1970 to more than 7,000 ac-ft/yr in 1995 through 2005. More than half of the pumping was "industrial," by Peabody Western Coal Company, and when Peabody reduced its pumping in and after 2006, the total pumping from the aquifer fell to around 4,000 ac-ft/yr. USGS recognizes a distinction between pumping from the N aquifer where it is unconfined in the western part of the area occupied by the aquifer (from Tuba City and Moenkopi around the mesa to Shonto), and in the area where water in the aquifer is under confined conditions. The Peabody wells, the HAMP wells, and the wells producing roughly one-half of the N-aquifer municipal supplies are in the confined area.

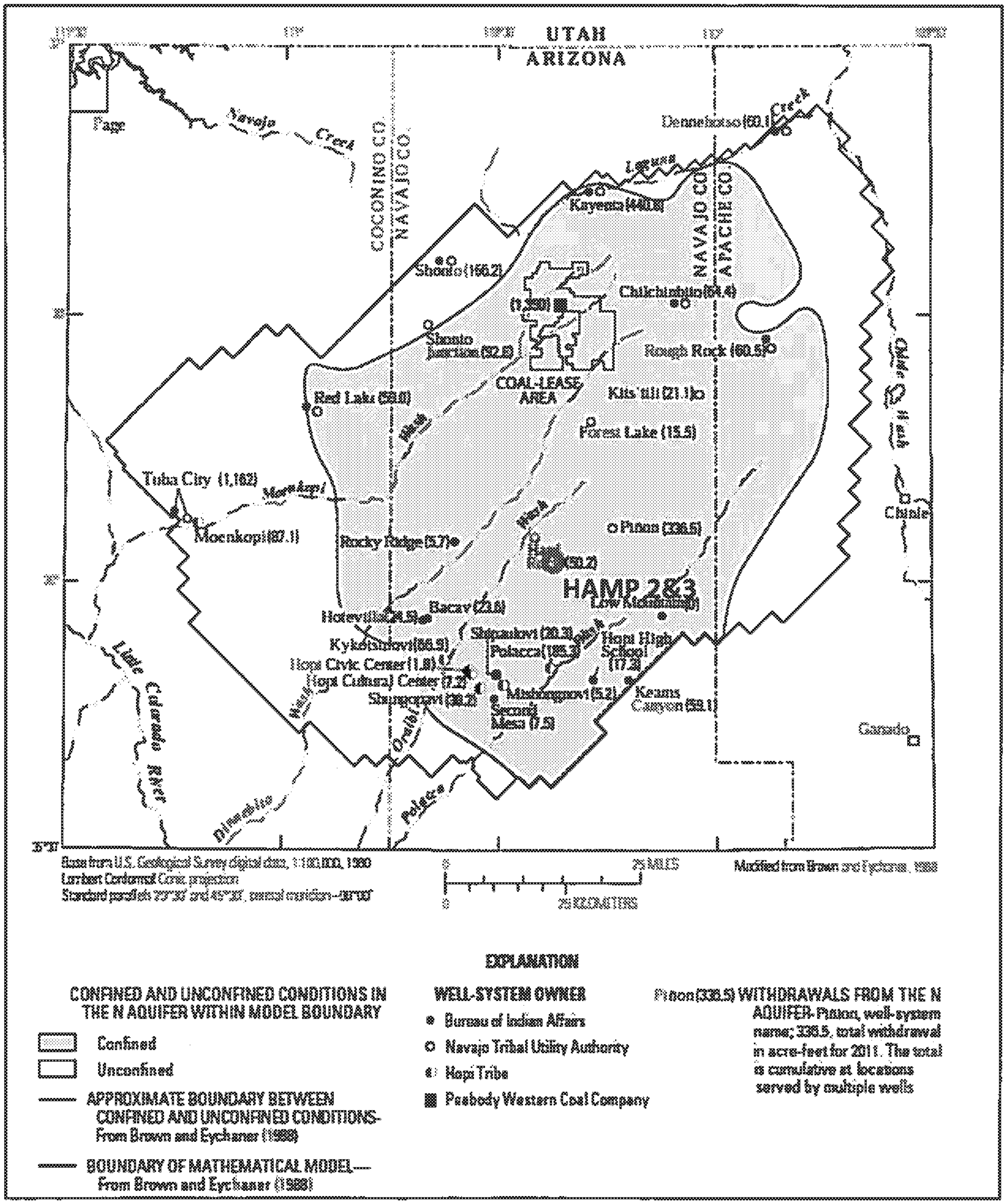

Figure 3. Map showing locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, 2011 (reproduced from Macy and Unema, 2013, fig. 4).

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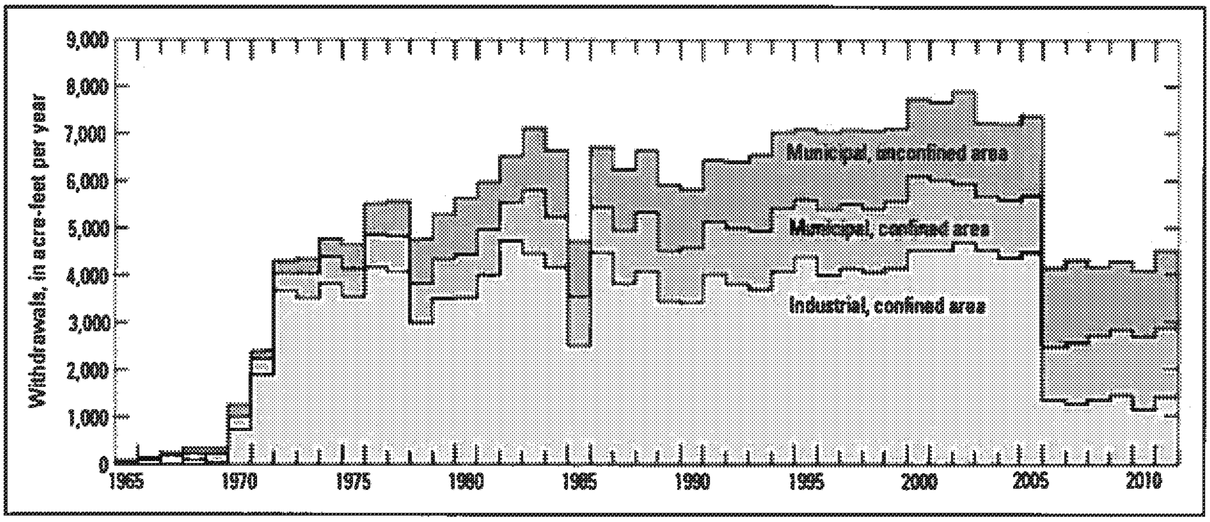

Figure 4 Plot showing annual withdrawals from the N aquifer, Black Mesa area, 1965-2011 (reproduced from Macy and Unema, 2013, fig. 3).

Historic Regional Drawdown: The USGS measures water levels continuously in six observation wells, and publishes periodic measurements in many other wells in the Black Mesa area. Observation well BM-5 is very close to HAMP Wells 2 (about 2.3 miles northeast of BM-5) and 3 (about 3.0 miles northeast), and has a continuous water-level record from 1972 to the present. The record is shown as Figure 5. There was little change in water level in 1972 and 1973, but the effects of significant pumping from the N aquifer began to be evident in 1974. From 1976 to early 1993, the water level declined at a relatively steady rate of about 3.35 ft/yr. From 1994 through 2006, the decline rate was less, at about 2.43 ft/yr, although the volumes pumped from the aquifer were somewhat greater. After pumping from the Peabody Western Coal Co. wells in the PWCC coal lease area was greatly reduced about the beginning of 2006, and following a lag of about 2 years, the water level in BM-5 ceased declining and appeared to be rising slightly by 2013.

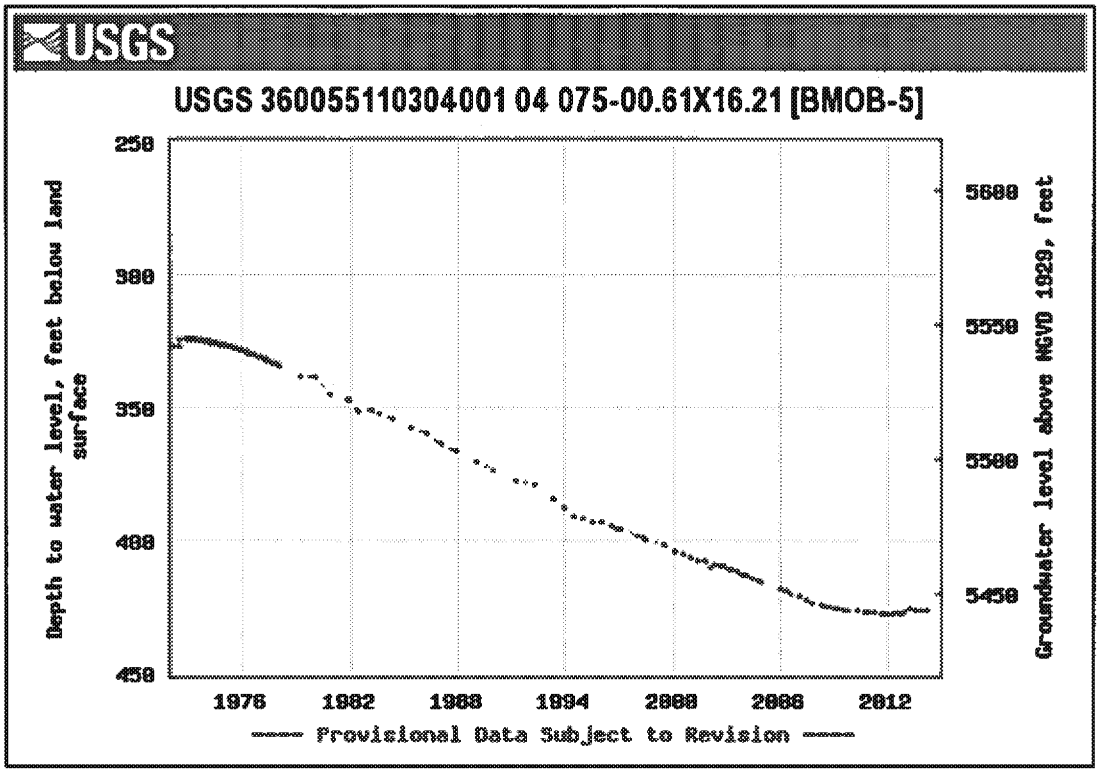

Figure 5. Graph showing depth to water in BM-5 observation well, Black Mesa area (from USGS GWSI).

USGS also gives a number of water-level measurements in the NTUA Hard Rock No. 1 well, about 2.7 miles northwest ~~of HAMP Well 2 and 3.5 miles northwest of HAMP~~ Well 3. The record is shown as Figure 6. A general decline is indicated between 1996 and 2002, but the trend is not clear, and the record ends before the reduction of pumping by Peabody. The Hard Rock well is a production well, and water levels would be affected by its own pumping and recovery. A pattern similar to that of observation well BM-5 is shown by observation well BM-6 (Fig. 7), between the HAMP wells and the Peabody operations. Overall change in water level in the N aquifer between 1965 and 2012 for wells in the Black Mesa area are shown on Figure 8.

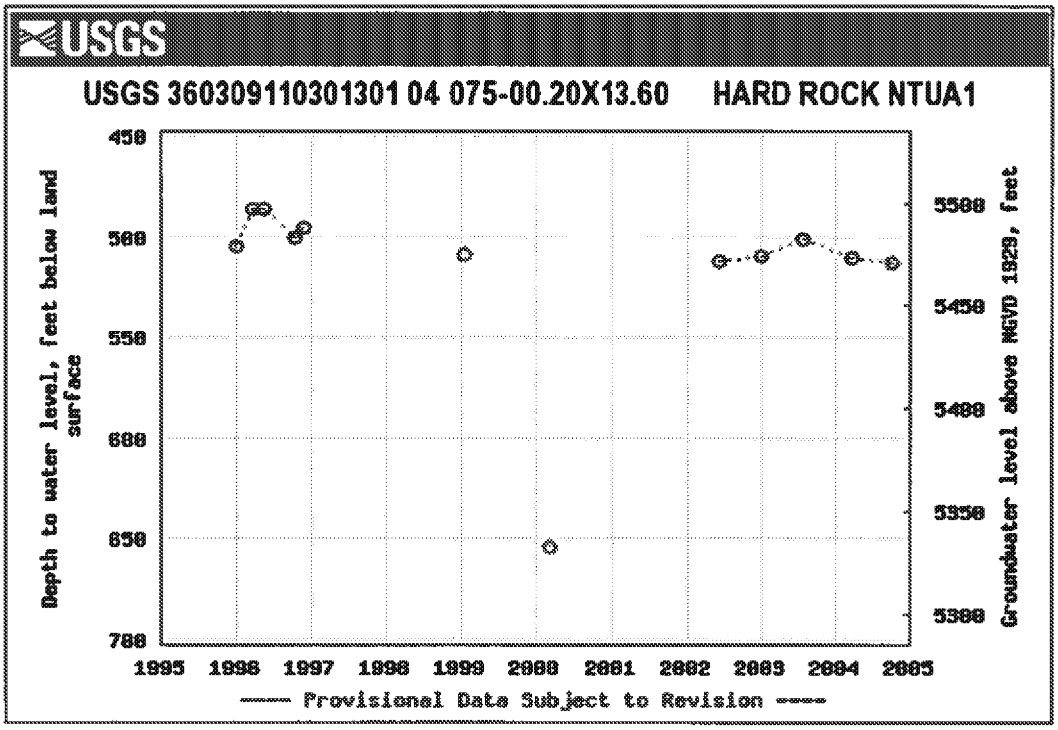

Figure 6. Graph showing depth to water in Hard Rock NTUA No. 1 Well, Black Mesa area (from USGS GWSI).

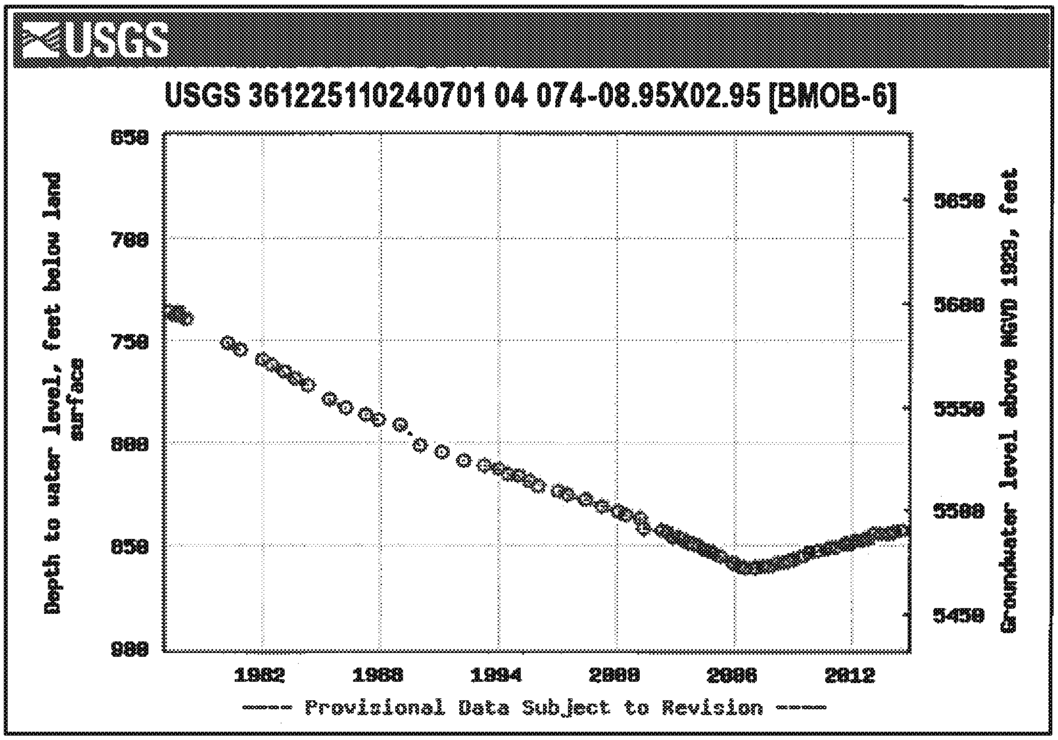

Figure 7. Graph showing depth to water in BM-6 observation well, Black Mesa area (from USGS GWSI).

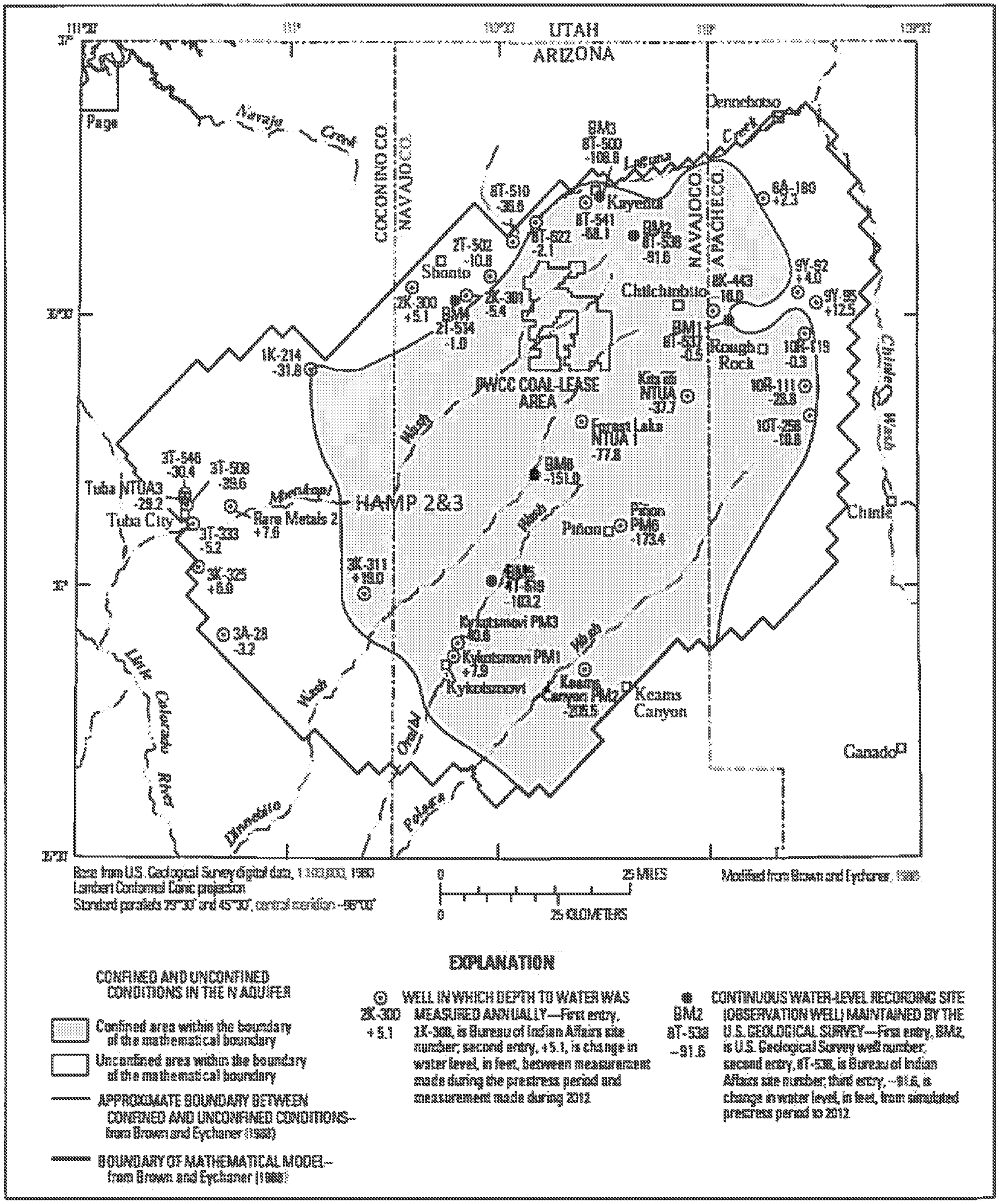

Figure 8. Map showing water-level changes in N-aquifer wells monitored by U.S. Geological Survey, Black Mesa area, 1965-2012 (reproduced from Macy and Unema, 2013, fig. 4). HAMP wells are about 2-1/2 miles east of observation well BM-5.

Future Pumping from HAMP Wells 2 and 3

A set of projections received from Adam Hughes of Indian Health Service (email dated August 4, 2014) indicates that combined pumping from HAMP Wells 2 and 3 to replace certain existing supplies for Shungopovi, Shipaulovi, Mishongnovi, and First Mesa consolidated villages (FMCV), and to provide for demand growth of 1.8 percent per year, would lead to average demand of 137.2 gpm (221.5 ac-ft/yr) in 2015, and 294.1 gpm (474.7 ac-ft/yr) in 2035. Design demand, in terms of estimated peak instantaneous pumping rates, are estimated at 205.8 gpm in 2015, and 392 gpm in 2035. The pump selected for each well has a design capacity of 413 gpm against 712 ft total head, providing capacity to meet the design demand with either well.

For the purpose of estimating future pumping water levels in the wells, the annual pumping is assumed to increase in equal annual steps from 2015 to 2035. The actual pumping water levels will vary from the estimates because demand will vary seasonally, and probably will not change smoothly from year to year. The combined pumping is assumed to be taken equally from the two wells.

Future Pumping from Other N-Aquifer Wells

The major influence on water levels in the N aquifer in the BM-5 observation well, and in the vicinity of the HAMP wells, appears to have been pumping by Peabody Western Coal Co. Members of the USGS staff (Stan Leake, quoted by Donald Pool in an email dated July 30, 2014) and one of Peabody's consultants (Richard Waddell of TetraTech GEO, telephone conversation on August 15, 2014), have indicated the expectation that Peabody's pumping is likely to continue into the future at the reduced level, around 1,400 ac-ft/yr.

It would appear that pumping from the HAMP wells will replace pumping from wells completed in the confined part of the N-aquifer now serving Shungopovi, Shipaulovi, Mishongnovi, and the First Mesa consolidated villages, a combined 213.59 ac-ft in 2013 (email from Adam Hughes, August 4, 2014). Cessation of pumping from these existing wells would also partly offset the drawdown in the HAMP wells.

Water-Level Change Attributable to Pumping from HAMP Wells 2 and 3 Alone

Future pumping water levels for HAMP Wells 2 and 3 were estimated using the Theis equation (Theis, 1935) with the aquifer characteristics described above. Annual pumping was assumed to rise by constant annual increments from 137.2 gpm (221.5 ac-ft/yr) in 2015, to 294.1 gpm (474.7 ac-ft/yr) in 2035, and the instantaneous pumping rate for each well was assumed to be a constant 415 gpm, with the actual demand met by varying the pumping time. Pumping was assumed to be apportioned equally between the wells. No regional water-level change over time, attributable to pumping by others or to change in recharge, was assumed. The drawdown effect of each well on the other was calculated using the average of the transmissivity values for the two wells. The resulting estimated pumping water levels are shown as Figures 9 and 10. The near straight-line trend, rather than a more typical nearly logarithmic trend, is attributable to the fact that the annual average pumping rate increases by equal amounts year by year.

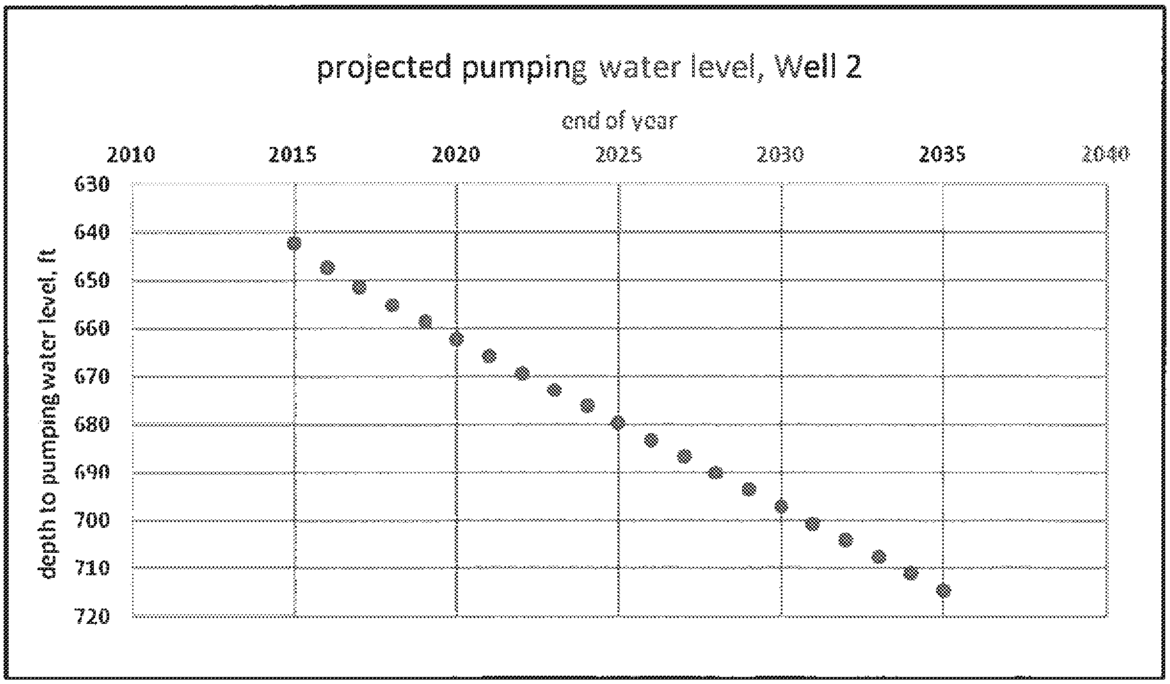

Figure 9. Graph showing projected pumping water level in HAMP Well 2, assuming a continuous increase in annual pumping from 137.2 gpm (221.5 ac-ft/yr) in 2015, to 294.1 gpm (474.7 ac-ft/yr) in 2035, divided equally between Well 2 and Well 3, with all production at an instantaneous rate of 415 gpm, and no regional water-level change.

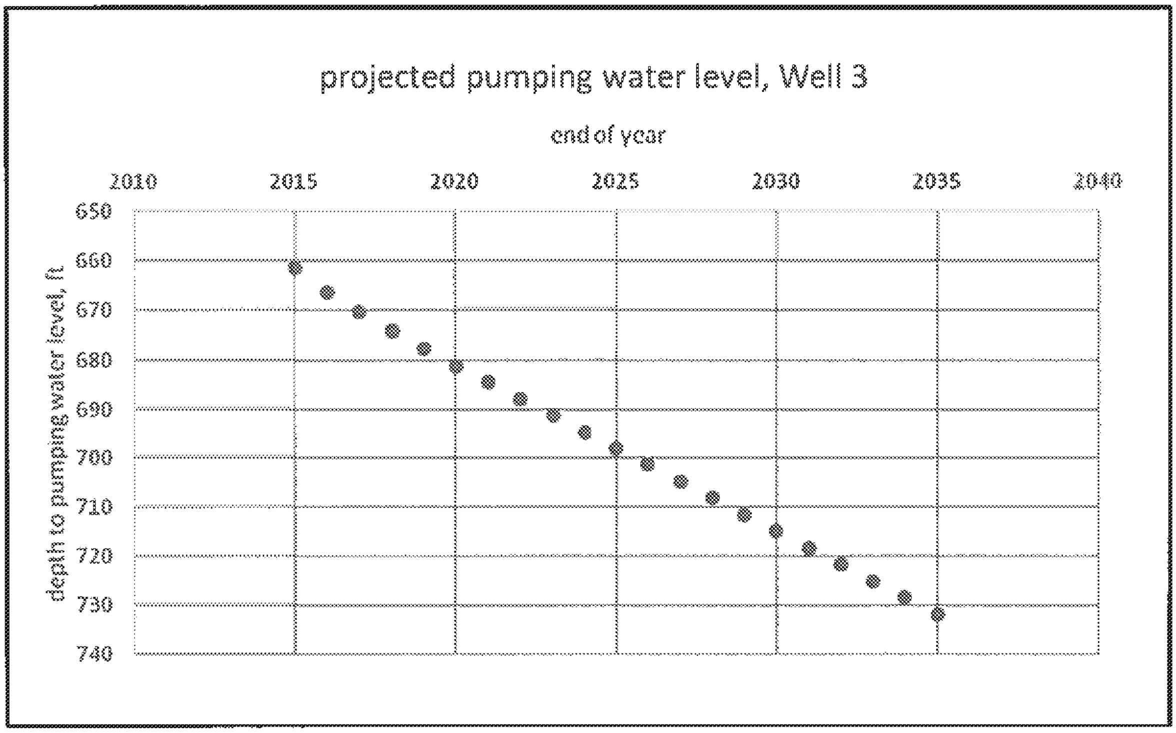

Figure 10. Graph showing projected pumping water level in HAMP Well 3, assuming a continuous increase in annual pumping from 137.2 gpm (221.5 ac-ft/yr) in 2015, to 294.1 gpm (474.7 ac-ft/yr) in 2035, divided equally between Well 2 and Well 3, with all production at an instantaneous rate of 415 gpm, and no regional water-level change.

Projected Change in Water Level and Capacity

Although there has been significant water-level decline in the confined part of the N aquifer since 1965, as shown by Figure 8, the decline in the vicinity of the HAMP wells ceased about 2008 as indicated by the record of observation well BM-5 (Fig. 5). In observation well BM-6, closer to the Peabody wells (Fig. 7), the water-level decline was reversed in 2007 and water levels have been rising since then. Measurements in the Hard Rock NTUA No. 1 Well (Fig. 6) show a decline between late 1996 and 2004, but the record is fragmentary and ends before the cessation of pumping by Peabody.

A prediction of future water levels in the HAMP wells can be made using a groundwater-flow model. A new model, either a completely new effort or a re-calibration of the model prepared by Brown and Eychaner (1988, itself a recalibrated version of their 1983 model), which is available to the public, is beyond the scope of this study. An inquiry has been made to TetraTech and Peabody seeking release of the 1999 version of the proprietary Peabody model, but there has been no reply as of this writing. However, Brown and Eychaner did carry out simulations for several sets of assumptions as to future pumping by Peabody, and for public supply. Their 1988 model predicted the actual drawdowns in observation well BM-5 very closely for the period 1974 through 2000, but under-predicted the drawdown between 2000 and 2010 by about 15 ft.

Brown and Eychaner's Projection B, which represents a 75-percent reduction of Peabody pumping after 2006 and cessation of Peabody pumping after 2011, and increases in withdrawals for Tribal communities of 2.5 percent per year in 5-year steps, would be a conservative approach to estimating future drawdowns and pumping levels in the HAMP wells. It would double-count some of the increases in withdrawals for Tribal communities, in that some of the increase would come from the HAMP wells themselves rather than the wells that existed at the time of the model study, and the effects of pumping from the HAMP wells on their own water levels would be accounted for in the projections shown in Figures 9 and 10. Adding the incremental water-level rises predicted by Brown and Eychaner's Projection B (shown on their fig. 23) to the future water levels shown in Figures 9 and 10 would lead to projected pumping water levels in HAMP Wells 2 and 3 as shown in Table 1. The rising water levels attributable to the cessation of Peabody pumping would again reverse about 2030, and by 2035 the pumping levels (under the demand assumptions described above for the HAMP wells) would be at about 698 and 715 ft, respectively. Clearly these projections involve many assumptions, and the predictions are subject to significant error.

Table 1. Projected pumping water levels in HAMP Wells 2 and 3 based on predicted levels due to in-well drawdown only, shown in Figures 9 and 10, adjusted to reflect water-level-change predictions of Brown and Eychaner (1988) groundwater-flow model, Projection B, for observation well BM-5 (their fig. 23)

	HAMP Well 2			HAMP Well 3		
year	predicted level due to in-well drawdown only, ft	water-level rise after 2015, ft	adjusted pumping depth to water, ft	predicted level due to in-well drawdown only, ft	water-level rise after 2015, ft	adjusted pumping depth to water, ft
2015	642	0	642	661	0	661
2020	662	10	653	681	10	671
2025	680	17	663	698	17	681
2030	697	18	679	715	18	697
2035	715	17	698	732	17	715

PROJECTED CHANGE IN WATER QUALITY

Arsenic concentration has been measured over time in the Piñon NTUA No. 1 and Forest Lake NTUA No. 1 wells, as shown in Figure 11. The data for the plots are taken from the series of USGS progress reports cited by Macy and Unema (2013). The Piñon well is located in the area where aquifer leakage is predicted (see Fig. 2), and the Forest Lake well is essentially on the boundary of the possible leakage area suggested by Lopes and Hoffmann (1997, fig. 4). TDS concentration over time for each well is shown in Figure 12. As might be expected, TDS concentration in water from the Piñon well has risen from somewhat less than 300 mg/L to more than 422 mg/L during the 29 years shown, while the TDS content of water from the Forest Lake well has varied over a wider range but without an evident trend.

Arsenic concentration appears to have increased in both the Piñon and Forest Lake wells, and at about the same rate, about 0.05 µg/L per year, although the production rates from the two wells are significantly different. Although the potential for leakage into the N aquifer in the vicinity of the HAMP wells is not completely understood, it would appear that the concentration in the D aquifer, at 2.9 µg/L, is less than in the N aquifer. Given that the concentrations in zones within the N aquifer are similar to each other, in the range 4.1 to 4.8 µg/L in HAMP Well 2, and that the concentrations in waters from the finished wells are within that range, it seems likely that, even if leakage occurs, arsenic concentrations would not rise above about 4.8 µg/L and might in fact decline.

The considerably higher TDS concentration in D-aquifer water, 1,390 mg/L, suggests that significant leakage through the Carmel Formation, if it occurs, might lead to some increase in TDS in either or both of the HAMP wells, even though arsenic concentration would not increase.

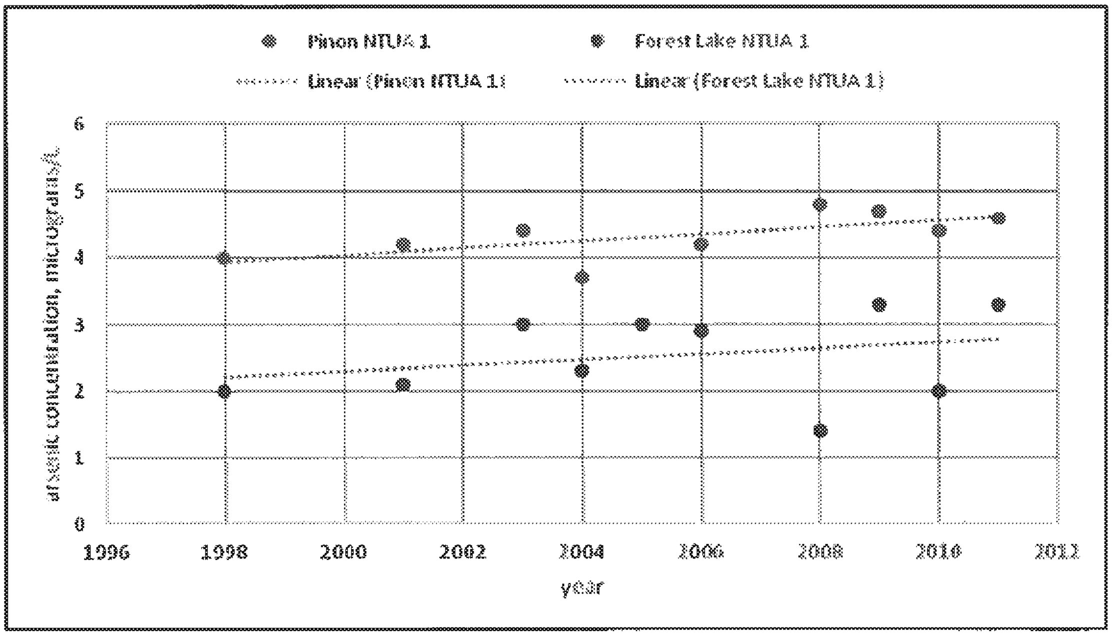

Figure 11. Arsenic concentration over time in Piñon NTUA No. 1 and Forest Lake NTUA No. 1 wells.

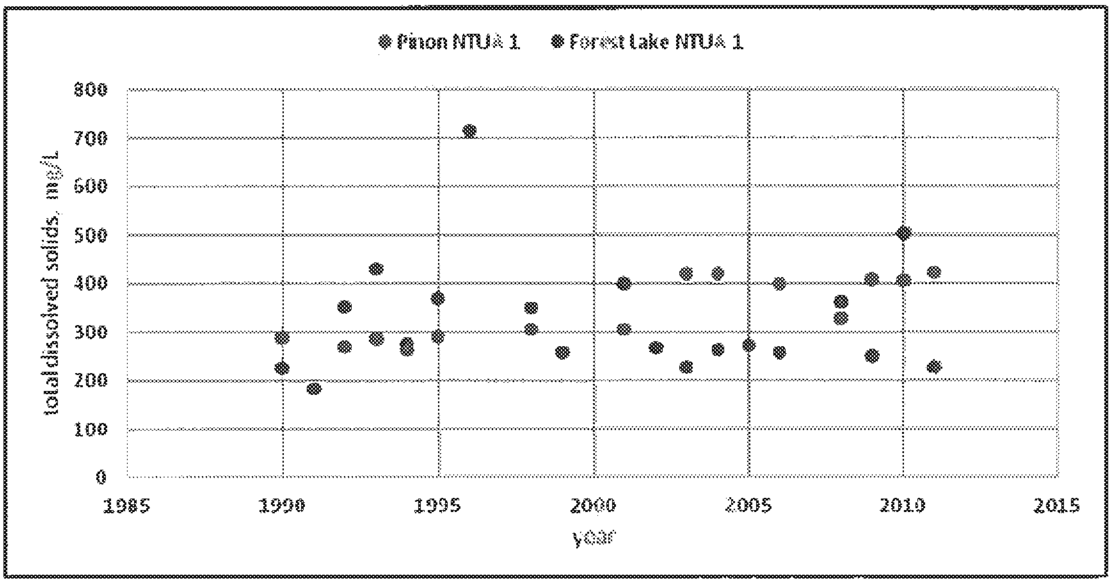

Figure 12. Total dissolved solids (TDS) concentration over time in Piñon NTUA No. 1 and Forest Lake NTUA No. 1 wells.

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